# ESTIMATING PRESTRESS LOSSES

by Paul Zia, H. Kent Preston, Norman L. Scott, and Edwin B. Workman

*Equations for estimating prestress losses due to various causes are presented for pretensioned and post-tensioned members with bonded and unbonded tendons. The equations are intended for practical design applications under normal design conditions as discussed in the commentary. Using the equations, sample computations are carried out for typical prestressed concrete beams selected from the literature. The comparison of the results shows fairly good agreement.*

**Keywords: beams (supports)**; creep properties; friction; post-tensioning; **prestressed concrete; prestressing** steels; **prestress loss**; pretensioning; shrinkage; stress relaxation; unbonded prestressing.

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## Introduction

The prestressing force in a prestressed concrete member continuously decreases with time. The factors which contribute to the loss of prestress are well known and they are clearly specified in the current Code.[1] The Code provisions for prestress losses (ACI 318-77, Section 18.6) are written both in performance language and in specific how-to-do-it procedures for losses due to friction. Without detailed analyses, design engineers are permitted to use lump sum loss values as suggested by the Code Commentary.[2] These lump sum loss values were originally proposed by the U.S. Bureau of Public Roads[4] and by the ACI-ASCE Committee 323.[3] Experiences have shown, however, that these lump sum values may not be adequate for some design conditions.

More recently, design recommendations have been developed by others[5,6,7,8,9,10,14] to implement the performance requirements of Section 18.6. Most procedures are relatively complex and convey the impression of an exactness that may not actually exist. The authors, members of ACI-ASCE Committee 423, prepared this report as a means of obtaining reasonably accurate values for the various code-defined sources of loss. A similar procedure was developed and adopted for use in bridge design.[11] It should be noted that the procedures described below are not intended for special structures such as water tanks.

## Computation of Losses

### Elastic Shortening of Concrete (ES)

For members with bonded tendons,

$$ES = K_{es} E_s \frac{f_{cir}}{E_{ci}} \qquad (1)$$

in which

$K_{es}$ = 1.0 for pretensioned members
$K_{es}$ = 0.5 for post-tensioned members when tendons are tensioned in sequential order to the same tension. With other post-tensioning procedures, the value for $K_{es}$ may vary from 0 to 0.5.

$$f_{cir} = K_{cir} f_{cpi} - f_g \qquad (2)$$

in which $K_{cir}$ = 1.0 for post-tensioned members
$K_{cir}$ = 0.9 for pretensioned members.

For members with unbonded tendons,

$$ES = K_{es} E_s \frac{f_{cpa}}{E_{ci}} \qquad (1A)$$

in which $f_{cpa}$ = average compressive stress in the concrete along the member length at the center of gravity of the tendons immediately after the prestress has been applied to the concrete.

### Creep of Concrete (CR)

For members with bonded tendons,

$$CR = K_{cr} \frac{E_s}{E_c} (f_{cir} - f_{cds}) \qquad (3)$$

in which

$K_{cr}$ = 2.0 for pretensioned members
$K_{cr}$ = 1.6 for post-tensioned members

For members made of sand lightweight concrete the foregoing values of $K_{cr}$ should be reduced by 20 percent.

For members with unbonded tendons,

$$CR = K_{cr} \frac{E_s}{E_c} f_{cpa} \quad (3A)$$

**Shrinkage of Concrete (SH)**

$$SH = 8.2 \times 10^{-6} K_{sh} E_s \left(1 - 0.06 \frac{V}{S}\right)(100 - RH) \quad (4)$$

in which

$K_{sh}$ = 1.0 for pretensioned members

or

$K_{sh}$ is taken from Table 1 for post-tensioned members.

**TABLE 1 — Values of $K_{sh}$ for post-tensioned members**

| Time after end of moist curing to application of prestress, days | 1 | 3 | 5 | 7 | 10 | 20 | 30 | 60 |
|---|---|---|---|---|---|---|---|---|
| $K_{sh}$ | 0.92 | 0.85 | 0.80 | 0.77 | 0.73 | 0.64 | 0.58 | 0.45 |

**Relaxation of Tendons (RE)**

$$RE = [K_{re} - J(SH + CR + ES)]\, C \quad (5)$$

in which the values of $K_{re}$, $J$ and $C$ are taken from Tables 2 and 3.

**TABLE 2 — Values of $K_{re}$ and $J$**

| Type of tendon* | $K_{re}$ | $J$ |
|---|---|---|
| 270 Grade stress-relieved strand or wire | 20,000 | 0.15 |
| 250 Grade stress-relieved strand or wire | 18,500 | 0.14 |
| 240 or 235 Grade stress-relieved wire | 17,600 | 0.13 |
| 270 Grade low-relaxation strand | 5,000 | 0.040 |
| 250 Grade low-relaxation wire | 4,630 | 0.037 |
| 240 or 235 Grade low-relaxation wire | 4,400 | 0.035 |
| 145 or 160 Grade stress-relieved bar | 6,000 | 0.05 |

*In accordance with ASTM A416-74, ASTM A421-76, or ASTM A722-75

**TABLE 3 — Values of $C$**

| $f_{pi}/f_{pu}$ | Stress relieved strand or wire | Stress-relieved bar or low relaxation strand or wire |
|---|---|---|
| 0.80 | | 1.28 |
| 0.79 | | 1.22 |
| 0.78 | | 1.16 |
| 0.77 | | 1.11 |
| 0.76 | | 1.05 |
| 0.75 | 1.45 | 1.00 |
| 0.74 | 1.36 | 0.95 |
| 0.73 | 1.27 | 0.90 |
| 0.72 | 1.18 | 0.85 |
| 0.71 | 1.09 | 0.80 |
| 0.70 | 1.00 | 0.75 |
| 0.69 | 0.94 | 0.70 |
| 0.68 | 0.89 | 0.66 |
| 0.67 | 0.83 | 0.61 |
| 0.66 | 0.78 | 0.57 |
| 0.65 | 0.73 | 0.53 |
| 0.64 | 0.68 | 0.49 |
| 0.63 | 0.63 | 0.45 |
| 0.62 | 0.58 | 0.41 |
| 0.61 | 0.53 | 0.37 |
| 0.60 | 0.49 | 0.33 |

**Friction**

Computation of friction losses is covered in Section 18.6.2 of ACI 318-77[1] and its Commentary.[2] When the tendon is tensioned, the friction losses computed can be checked with reasonable accuracy by comparing the measured elongation and the prestressing force applied by the tensioning jack.

**Commentary**

Determination of loss of prestress in accordance with Section 18.6.1 of ACI 318-77 usually involves complicated and laborious procedures because the rate of loss due to one factor, such as relaxation of tendons, is continually altered by changes in stress due to other factors such as shrinkage and creep of concrete. Rate of creep is, in turn, altered by the change in tendon stress. Many of these factors are further dependent upon such uncertainties as material properties, time of loading, method of curing of concrete, environmental conditions, and construction details.

The equations presented are intended for a reasonable estimate of loss of prestress from the various sources. They are applicable for prestressed members of normal designs with an extreme fiber compressive stress in the precompressed tensile zone under the full dead load condition ranging from 350 psi (2.41 MPa) to 1750 psi (12.1 MPa) using a minimum concrete cylinder strength $f_c'$ of 4000 psi (27.6 MPa) and a unit weight of concrete of at least 115 pcf (1842.3 kg/m$^3$). For unusual design conditions, a more detailed procedure should be considered.[8]

Actual losses, greater or smaller than the estimated values, have little effect on the design strength of a flexural member with bonded tendons unless the final tendon stress after losses is less than 0.5 $f_{pu}$. However, they affect service load behavior, such as deflection and camber, connections, or cracking load. Over-estimation of prestress losses can be almost as detrimental as under-estimation, since the former can result in excessive camber and horizontal movement.

Careful consideration of losses may be required for simply supported, slender members which may be sensitive to small changes in deflections. For example, shallow beams supporting flat roofs may be subject to ponding if sensitive to deflection.

### Elastic Shortening of Concrete

Prestress loss due to elastic shortening of concrete is directly proportional to the concrete strain at the center of gravity of prestressing force immediately after transfer. For example, for members of simple span,

$$f_{cir} = K_{cir} f_{cpi} - f_g$$

$$= K_{cir}\left(\frac{P_{pi}}{A_c} + \frac{P_{pi}e^2}{I_c}\right) - \frac{M_G e}{I_c}$$

The different values for the coefficients $K_{es}$ and $K_{cir}$ account for the difference in the order of transfer. In applying Equation (2), the transformed section of a member may be used in lieu of the gross concrete section.

### Creep of Concrete

Part of the initial compressive strain induced in the concrete immediately after transfer is reduced by the tensile strain resulting from the superimposed permanent dead load. Loss of prestress due to creep of concrete is therefore proportional to the net permanent compressive strain in the concrete.

For prestressed members made of sand lightweight concrete, there is a significantly larger amount of loss due to elastic shortening of concrete because of its lower modulus of elasticity, resulting in an overall reduction in loss due to creep. This effect is accounted for by a 20 percent reduction of the creep coefficient. For members made of all lightweight concrete, special consideration should be given to the properties of the particular lightweight aggregate used.

### Unbonded Tendons

Since an unbonded tendon can slide within its duct, for most flexural members it does not undergo the same stress induced strain changes as the concrete surrounding it. For this reason, the average compressive stress, $f_{cpa}$, in the concrete is suggested for use in evaluating prestress losses due to elastic shortening and creep of concrete. This procedure relates the elastic shortening and creep of concrete prestress losses for unbonded tendons to the average member strain, rather than the strain at the point of maximum moment. The somewhat higher residual tensile stress in an unbonded tendon logically results in somewhat higher loss due to steel relaxation.

### Shrinkage of Concrete

Shrinkage strain developed in a concrete member is influenced, among other factors, by its volume/surface ratio and the ambient relative humidity. Thus, the effective shrinkage strain $\varepsilon_{sh}$ is obtained by multiplying the basic ultimate shrinkage strain $\varepsilon_{sh}$ of concrete, taken as $550 \times 10^{-6}$, by the factors $(1 - 0.06\ V/S)$ and $(1.5 - 0.015RH)$. Thus

$$\varepsilon_{sh} = 550 \times 10^{-6}\left(1 - 0.06\frac{V}{S}\right)\left(1.5 - 0.015RH\right)$$

$$= 8.2 \times 10^{-6}\left(1 - 0.06\frac{V}{S}\right)\left(100 - RH\right)$$

The loss of prestress due to shrinkage is therefore the product of the effective shrinkage $\varepsilon_{sh}$ and the modulus of elasticity of prestressing steel. The factor $K_{sh}$ accounts for the reduction in shrinkage due to increased curing period.

It should be noted that for some lightweight concrete, the basic ultimate shrinkage strain $\varepsilon_{sh}$ may be greater than the value used here. In addition, the following tabulated correction factors for the effect of the ambient relative humidity may be used in lieu of the expression $(1.5 - 0.015\ RH)$:

| Ave. Ambient $RH$ (%) | Correction Factor |
|---|---|
| 40 | 1.43 |
| 50 | 1.29 |
| 60 | 1.14 |
| 70 | 1.00 |
| 80 | 0.86 |
| 90 | 0.43 |
| 100 | 0.00 |

### Relaxation of Tendons

Relaxation of a prestressing tendon depends upon the stress level in the tendon. Basic relaxation values $K_{re}$ for the different kinds of steel are shown in Table 2. However, because of other prestress losses, there is a continual reduction of the tendon stress, thus causing a reduction in relaxation. The reduction in tendon stress due to elastic shortening of concrete occurs instantaneously. On the other hand, the reduction due to creep and shrinkage takes place in a prolonged period of time. The factor $J$ in Equation (5) is specified to approximate these effects.

### Maximum Loss

The total amount of prestress loss due to elastic shortening, creep, shrinkage, and relaxation need not be more than the values given below if the tendon stress immediately after anchoring does not exceed 0.83 $f_{py}$:

| Type of strand | Maximum Loss psi (MPa) Normal Concrete | Lightweight Concrete |
|---|---|---|
| Stress relieved strand | 50,000 (345) | 55,000 (380) |
| Low-relaxation strand | 40,000 (276) | 45,000 (311) |

### Seating Loss at Anchorage

Many types of anchorage require that the anchoring device "set" from 1/8 in. (3.2 mm) to ¼ in. (6.4 mm) in order to transfer force from the tendon to the concrete. The actual seating loss varies with field technique and anchor type. As the seating loss is small, it is not practicable to measure it with accuracy; therefore it is important to recognize the effects of maximum and minimum values of seating loss. Usually long tendons with curvature will be unaffected by seating loss, since the required tendon elongation generally necessitates stressing to the maximum initial value to overcome friction. For short tendons, however, the elongation corresponding to the range of stress of 70 percent to 80 percent of the ultimate is too small to nullify seating loss, and attempts to obtain the necessary elongation would require exceeding the 80 percent limit with possible rupture of the tendon. Thus, the

**TABLE 4 — Beam data from reference 6**

| Beam No. | Beam section | Deck width x thickness & weight | Transfer at (days) | Cast deck (days) | No. of strands ϕ ½ in. | Initial stress $f_{pi}$ (ksi) | $f_{cir}$ (psi) | $f_{cds}$ (psi) | *RH* % | *V/S* (in.) |
|---|---|---|---|---|---|---|---|---|---|---|
| HG1 | AASHTO-III | No Deck | 2½ | — | 20 | 189 | 1411 | 0 | 80 | 4.06 |
| HG2 | AASHTO-III | 96x8-800 | 1 | 90 | 22 | 189 | 1622 | 765 | 80 | 4.06 |
| HG3 | AASHTO-III | 60x5-310 | 2½ | 90 | 22 | 189 | 1596 | 297 | 50 | 4.06 |
| HG4 | AASHTO-III | 96x8-800 | 7 | 90 | 24 | 189 | 1721 | 761 | 80 | 4.06 |
| HG5 | 8 ft Single Tee | 96x2-200 | 2½ | 90 | 12 | 189 | 1125 | 695 | 80 | 2.07 |
| HG6 | 8 ft Double Tee | 96x2-200 | 2½ | 90 | 24 | 189 | 1600 | 696 | 80 | 1.87 |
| HG7 | 54 in. I-Beam | 60x5-310 | 2½ | 90 | 30 | 189 | 1554 | 309 | 80 | 3.60 |
| HG8 | 8 ft Single Tee | 96x2-200 | 2½ | 90 | 12 | 205* | 1469 | 695 | 80 | 2.07 |
| HG9 | AASHTO-III | 96x8-800 | 2½ | 90 | 24 | 205* | 2020 | 761 | 80 | 4.06 |
| HG10 | 54 in. I-Beam | 96x8-800 | 2½ | 90 | 30 | 205* | 1646 | 796 | 80 | 3.60 |

*Low relaxation strand

$E_s = 28 \times 10^6$ psi, $E_{ci} = 3.5 \times 10^6$ psi and $E_c = 4.2 \times 10^6$ psi

**TABLE 5 — Comparison of loss values based on proposed procedure with theoretical results obtained by Hernandez and Gamble (H & G)**

| Beam No. | Method | *ES* (psi) | *CR* (psi) | *SH* (psi) | *RE* (psi) | Total (psi) |
|---|---|---|---|---|---|---|
| HG1 | Proposed | 11288 | 18813 | 3473 | 14964 | 48538 |
| | H & G | 9057 | 17656 | 3836 | 18699 | 49219 |
| HG2 | Proposed | 12976 | 11427 | 3473 | 15819 | 43695 |
| | H & G | 10364 | 15327 | 3836 | 18085 | 47614 |
| HG3 | Proposed | 12768 | 17320 | 8683 | 14184 | 52955 |
| | H & G | 10202 | 25840 | 7195 | 16743 | 59981 |
| HG4 | Proposed | 13768 | 12800 | 3473 | 15494 | 45535 |
| | H & G | 10965 | 11793 | 3836 | 19370 | 45966 |
| HG5 | Proposed | 9000 | 5733 | 4022 | 17187 | 35942 |
| | H & G | 8170 | 9374 | 5348 | 18949 | 41842 |
| HG6 | Proposed | 12800 | 12053 | 4077 | 15661 | 44591 |
| | H & G | 11264 | 16069 | 5348 | 16840 | 49522 |
| HG7 | Proposed | 12432 | 16600 | 3600 | 15105 | 47737 |
| | H & G | 9984 | 17285 | 3723 | 18414 | 49408 |
| HG8 | Proposed | 11752 | 10320 | 4022 | 4154 | 30248 |
| | H & G | 10295 | 16192 | 5348 | 4558 | 36393 |
| HG9 | Proposed | 16160 | 16787 | 3473 | 3720 | 40140 |
| | H & G | 12816 | 19780 | 3835 | 4564 | 40996 |
| HG10 | Proposed | 13168 | 11333 | 3600 | 4070 | 32171 |
| | H & G | 10552 | 15154 | 3835 | 4368 | 33910 |

seating loss in short tendons should be deducted from the prestress that is applied to the tendon by the tensioning jack.

### Restraining Effect of Adjoining Elements

Loss of prestress to adjoining elements of the structure must be properly evaluated. If a member is in contact with or attached to another member during the post-tensioning operation, there can be a transfer of prestressing force from one member to the other.

After the structure is complete, there will be volume changes due to creep and shrinkage of concrete and to variations of temperature. If the member can not move freely to accommodate these volume changes, there will be a transfer of prestressing force from the prestressed member to the restraining member and a resultant loss of prestress in the prestressed member.

## Sample Computations

In order to assess whether the proposed equations are appropriate for estimating prestress losses, the following sample computations have been prepared for typical prestressed beams selected from the test program reported by Hernandez and Gamble.[6] The pertinent data regarding the beams are summarized in Table 4. With the procedures described herein, the computed prestress loss values are compared with the theoretical values obtained by Hernandez and Gamble as shown in Table 5. It should be noted that the theoretical predictions made by Hernandez and Gamble were based on their revised rate of creep method treated as a step-by-step numerical integration procedure with short time intervals. The unit creep and shrinkage strains versus time relationships were based on the 1970 CEB recommendations[13] which were found to be comparable to the field data obtained in their study. It can be seen that the comparisons show fairly good agreement.

Additional sample computations have been carried out on selected double T beams listed in the PCI *Design Handbook*. The double T beam properties are summarized in Table 6. The results are shown in Table 7. It is interesting to note that for those slender beams (i.e., Z2 and S2) with very small superimposed permanent load and under fairly low humidity, the total loss of prestress would be quite significant. With more superimposed permanent load and/or higher humidity, the total prestress loss value is reduced. (Compare S1a and S1b with S1, or S2a and S2b with S2, or S3a with S3.) Comparison of S3a with S4 also shows that the total prestress loss value is somewhat increased for the beam made of lightweight concrete.

**TABLE 7 — Results of sample computations for pretensioned beams from PCI *Design Handbook***

| Beam No. | *ES* (psi) | *CR* (psi) | *SH* (psi) | *RE* (psi) | Total (psi) |
|---|---|---|---|---|---|
| Z1 | 6896 | 5693 | 6268 | 17171 | 36028 |
| Z2 | 16064 | 19613 | 10653 | 13051 | 59381 |
| Z3 | 3784 | 5400 | 5340 | 17821 | 32345 |
| S1 | 4352 | 7253 | 10681 | 16657 | 38943 |
| S1a | 4352 | 4880 | 10681 | 17013 | 36926 |
| S1b | 4352 | 4880 | 5341 | 17814 | 32387 |
| S2 | 16280 | 27133 | 10447 | 11921 | 65781 |
| S2a | 16280 | 18933 | 10447 | 13151 | 58811 |
| S2b | 16280 | 18933 | 5224 | 13934 | 54371 |
| S3 | 2816 | 4693 | 5224 | 18090 | 30823 |
| S3a | 2816 | 3061 | 5224 | 18335 | 29436 |
| S4 | 5622 | 5486 | 5224 | 17550 | 33882 |

$E_s = 28 \times 10^6$ psi
For normal wt. concrete: $E_{ci} = 3.5 \times 10^6$ psi $E_c = 4.2 \times$
For light wt. concrete: $E_{ci} = 2.5 \times 10^6$ psi $E_c = 3.1 \times 1$

**TABLE 6 — Beam data from PCI *Design Handbook* for sample computations**

| Beam No. | Beam Sec. | Span (ft) | Initial prestress $P_{pi}$ (kips) | Initial stress $f_{pi}$ (ksi) | Ecc. $e$ (in.) | D. L. (lbs/ft) | Superimposed assumed permanent load (lbs/ft) | $f_{cir}$ (psi) | $f_{cds}$ (psi) | *RH* (%) | *V/S* (in.) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Z1 | 8DT24 | 62 | 230.6 | 189 | 14.15 | 418 | 112 | 862 | 435 | 70 | 1.5 |
| Z2 | 4DT14 | 50 | 173.9 | 189 | 7.34 | 188 | 56 | 2008 | 537 | 50 | 1.2 |
| Z3 | 8DT12 | 28 | 115.7 | 189 | 4.13 | 299 | 40 | 473 | 68 | 75 | 1.16 |
| S1 | 8DT12 | 26 | 115.7 | 189 | 4.13 | 299 | 0 | 544 | 0 | 50 | 1.16 |
| S1a | 8DT12 | 26 | 115.7 | 189 | 4.13 | 299 | 120 | 544 | 178 | 50 | 1.16 |
| S1b | 8DT12 | 26 | 115.7 | 189 | 4.13 | 299 | 120 | 544 | 178 | 75 | 1.16 |
| S2 | 8DT24 | 72 | 404.8 | 189 | 13.65 | 418 | 0 | 2035 | 0 | 50 | 1.5 |
| S2a | 8DT24 | 72 | 404.8 | 189 | 13.65 | 418 | 120 | 2035 | 615 | 50 | 1.5 |
| S2b | 8DT24 | 72 | 404.8 | 189 | 13.65 | 418 | 120 | 2035 | 615 | 75 | 1.5 |
| S3 | 8DT24 | 42 | 115.7 | 189 | 12.15 | 418 | 0 | 352 | 0 | 75 | 1.5 |
| S3a | 8DT24 | 42 | 115.7 | 189 | 12.15 | 418 | 80 | 352 | 122.4 | 75 | 1.5 |
| S4 | 8LDT24 | 42 | 115.7 | 189 | 12.15 | 320 | 80 | 502 | 122.4 | 75 | 1.5 |

## Conclusions

Simple equations for estimating losses of prestress have been proposed which would enable the designer to estimate the various types of prestress loss rather than a lump sum value. It is believed that these equations, intended for practical design applications, would provide fairly realistic values for normal design conditions. For unusual design situations and special structures, more detailed and complex numerical analysis should be used.

## Notation

$A_c$ = area of gross concrete section at the cross section considered

$A_{ps}$ = total area of prestressing tendons

$CR$ = stress loss due to creep of concrete

$C$ = a factor used in Eq. (5), see Table 3

$e$ = eccentricity of center of gravity of tendons with respect to center of gravity of concrete at the cross section considered

$E_{ci}$ = modulus of elasticity of concrete at time prestress is applied

$E_c$ = modulus of elasticity of concrete at 28 days

$E_s$ = modulus of elasticity of prestressing tendons. Usually 28,000,000 psi

$ES$ = stress loss due to elastic shortening of concrete

$f_{cds}$ = stress in concrete at center of gravity of tendons due to all superimposed permanent dead loads that are applied to the member after it has been prestressed

$f_{cir}$ = net compressive stress in concrete at center of gravity of tendons immediately after the prestress has been applied to the concrete. See Eq. (2)

$f_{cpa}$ = average compressive stress in the concrete along the member length at the center of gravity of the tendons immediately after the prestress has been applied to the concrete

$f_{cpi}$ = stress in concrete at center of gravity of tendons due to $P_{pi}$

$f_g$ = stress in concrete at center of gravity of tendons due to weight of structure at time prestress is applied

$f_{pi}$ = stress in tendon due to $P_{pi}$, $f_{pi} = P_{pi}/A_{ps}$

$f_{pu}$ = ultimate strength of prestressing tendon, psi

$I_c$ = moment of inertia of gross concrete section at the cross section considered

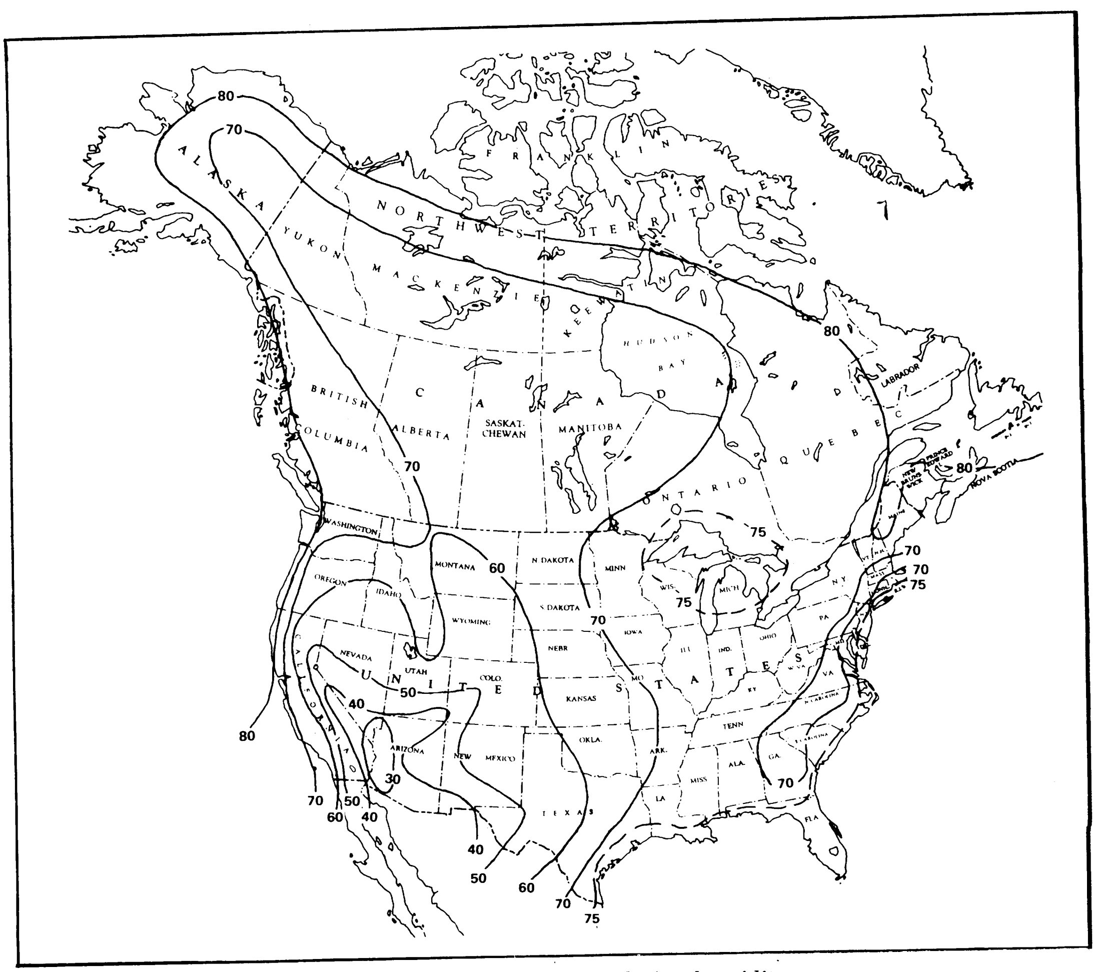
$J$ = a factor used in Eq. (5), See Table 2

$K_{cir}$ = a factor used in Eq. (2)

$K_{cr}$ = a factor used in Eq. (3)

$K_{es}$ = a factor used in Eq. (1)

$K_{re}$ = a factor used in Eq. (5). See Table 2.




*Annual average ambient relative humidity*

$M_G$ = bending moment due to dead weight of member being prestressed and to any other permanent loads in place at time of prestressing

$P_{pi}$ = prestressing force in tendons at critical location on span after reduction for losses due to friction and seating loss at anchorages but before reduction for *ES, CR, SH,* and *RE.*

*RE* = stress loss due to relaxation of tendons

*RH* = average relative humidity surrounding the concrete member. See annual average ambient relative humidity map appended.

*SH* = stress loss due to shrinkage of concrete

*V/S* = volume to surface ratio. Usually taken as gross cross-sectional area of concrete member divided by its perimeter.

1 in. = 25.4 mm
1 ft = .3048 m
1 psi = .0069 MPa
1 ksi = 70.31 kgf/em$^2$

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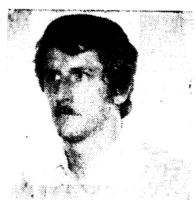
*FACI* ***Paul Zia*** *is professor and head of the Department of Civil Engineering, North Carolina State University at Raleigh. He has been an active member and chairman of many ACI committees including TAC and ACI-ASCE Committee 423, Prestressed Concrete, and is currently an ACI director and chairman of ACI-ASCE Committee 445, Shear and Torsion. He has authored numerous papers and received many awards.*

*FACI* ***Norman L. Scott*** *is president of the Consulting Engineers Group, Inc., Glenview, Ill. He is currently chairman of the ACI Institute and Industry Committee and is past chairman of ACI-ASCE Committee 423, Prestressed Concrete.*

*ACI member* ***H. Kent Preston*** *is a senior consultant with Wiss, Janney, Elstner and Associates, Inc., and is consultant to Florida Wire and Cable Company. He is a member of ACI-ASCE Committee 423, Prestressed Concrete. Since 1950 he has authored and coauthored numerous publications in various professional journals and three textbooks on the subject of prestressed concrete.*



***Edwin B. Workman*** *is owner of Edworkman, S. E. Structural Engineer, Inc., Canoga Park, Calif. He has been an ACI member since 1970 and is a member of ACI-ASCE Committee 423, Prestressed Concrete.*